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# **Re-examination of Mixed Media Communication: The Impact of Voice, Data Link, and Mixed Air Traffic Control Environments on the Flight Deck**

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## Summary

A simulation in the B747-400 was conducted at NASA Ames Research Center that compared how crews handled voice and data link air traffic control (ATC) messages in a single medium versus a mixed voice and data link ATC environment. The interval between ATC messages was also varied to examine the influence of time pressure in voice, data link, and mixed ATC environments. For messages sent via voice, transaction times were lengthened in the mixed media environment for closely spaced messages. The type of environment did not affect data link times. However, messages times were lengthened in both single and mixed-modality environments under time pressure. Closely spaced messages also increased the number of requests for clarification for voice messages in the mixed environment and review menu use for data link messages. Results indicated that when time pressure is introduced, the mix of voice and data link does not necessarily capitalize on the advantages of both media. These findings emphasize the need to develop procedures for managing communication in mixed voice and data link environments.

## Introduction

Re-examination of Mixed media Communication: The Impact of Voice, Data Link and Mixed Air Traffic Control Environments on the Flight Deck Controller Pilot Data Link Communication (CPDLC) is a newly implemented means of communication between controllers and pilots using electronic messaging. While the concept of data link is not new and has been researched for over two decades, Very High Frequency (VHF) radio remains the primary source for the transfer of information between the air traffic service provider and the aircraft. A number of studies examining incident and accident reports have identified problems arising from voice communication, including those associated with frequency congestion and communication errors. (Billings & Cheaney, 1981; Lee & Lozito, 1989; Morrow & Rodvold, 1998).

Furthermore, the increase in aircraft requiring the use of the National Airspace System (NAS) continues to exacerbate the problem of already crowded frequencies. These issues have led to a renewed effort by the Federal Aviation Administration (FAA) and the aviation industry to find relief for the overburdened system. Operational use of CPDLC in a limited South Pacific oceanic environment began in 1995 and has since expanded into other oceanic regions (FAA, 1999). The European aviation community began conducting its trials of data link in 1995 and continues to broaden its program (Eurocontrol, 2000). The use of data link in the domestic en route environment has now been called for to augment conventional radio communication in an effort to help alleviate some of the constraints of the current system and to establish the foundation for enabling subsequent technologies.

Because data link will be supplemental to voice communication, a mixed environment where pilots and controllers will be required to move from radio to data link media is anticipated (RTCA, 2000). Voice amendments to data link clearances can also be foreseen due to potential difficulties with pilot-controller negotiations via data link communication (Air Transportation Association [ATA], 1992). Early data link research concentrated on single medium voice or data link environments. Research findings have shown an increase in accuracy and consistency for data link at the cost of speed for the transfer of information (see Kerns, 1991, 1999 for a review). Still other studies have examined a limited mixed voice-data link environment. For example, when using data link for redundancy of a voice message, Talotta et al., (1988) found that the controllers workload increased. Hinton and Lohr (1988) examined an environment where specific messages, such as heading and altitude clearances, were issued through data link, whereas other specific clearances were delivered via voice communication. The participants in the study found this mix of voice and data link to be pretty "natural". Kerns (1999)

reports in her research summary that a dual-media environment of voice and data link requires fewer total transmissions than the all-voice environment. While research has indicated a reluctance by pilots to use data link in the busy terminal area and for non-routine transmissions (Kerns, 1999), little research exists that examines how the two media will best coexist.

There has been relevant research that may illustrate some potential issues around a mixed media environment. Morrow and Rodvold (1993) found that the time interval between messages impacts both voice and textual data link communication. Results showed that breaking down long messages into pairs of shorter messages with a brief interval in between reduced the overall number of voice clarifications in a voice environment, yet increased the number of voice clarifications in the data link environment. No ability to review messages was available for this study requiring all clarifications to be handled on the voice channel. The study also revealed longer overall acknowledgement times for both voice and data link when there was a short interval between messages. Underscoring the importance of these findings, researchers (Cardosi, 1993; Morrow, Lee, & Rodvold, 1993) have emphasized that in the voice environment, complex messages overtax pilots' working memory and have recommended that controllers reduce the length of their messages. Creating shorter messages may increase the number of clearances that must be given in a short time period. The mixed data link-voice environment that requires the user to switch modalities and communication procedures during short intervals may magnify the problems associated with time pressure in air-ground communication.

Additionally, voice and data link communication have different procedural constraints. One such constraint is the ability to respond to the message. Because voice is more temporal and often more salient than the visual modality (Sorkin, 1987), a voice clearance

may draw a more immediate response. In contrast, a suggested benefit of data link is its flexible access where the pilot can manage the communication task around other flight duties (Kerns, 1991). Additionally, sequential constraints differ for the two different media. For radio communication the entry of the clearance data is flexible and can be implemented simultaneously while receiving the voice communication. The textual data link environment, in contrast, requires a fixed sequence of discrete steps for message handling. However, the permanent nature of the data link message allows for flexibility of when the message is retrieved.

Voice and data link environments have special characteristics associated with them. Combining the two media in a mixed environment may alter the characteristics in a way that does not maintain the advantages of each medium separately. To examine whether there may be an impact of switching between voice and data link communication due to the change in modality and communication procedures, McGann, Morrow, Rodvold, and Mackintosh (1998) examined the flight deck perspective of voice and data link communication in both single medium and mixed media environments. The interval between air traffic control (ATC) messages was also varied to look at the influence of time pressure in voice, data link, and mixed ATC environments. Results from this part-task simulation indicated that voice transaction times were longer in the mixed than in the single medium environment, while data link transaction times were unaffected by the environment. Time pressure resulting from short intervals between messages increased data link transaction times in both the pure data link and mixed data link-voice environments. However, message interval influenced voice communication only in the mixed environment and only when a voice clearance closely followed a data link message. Closely spaced messages also increased the number of requests for clarification for voice messages and review menu use for data link messages. Pilots appeared to handle all

communication sequentially, closing out a data link message prior to attending to the voice message. Because the voice clearance was ephemeral, pilots had trouble remembering the voice message and this resulted in more clarifications.

There were some potential weaknesses to the previous study by McGann et. al (1998). The testing environment used for the experiment was a part-task simulator. Although the realism for the flight deck environment was good, it did not have the full set of tools and displays that would be available on a commercial flight deck. In addition, in this experiment the simulator supported single pilot operations in the earlier investigation. One participant performed all aviation, navigation, and communication tasks, including data link operations. Thus, workload was likely different from what would be expected in an actual commercial aircraft with multiple crewmembers.

The present study was designed to follow up on the part-task study described above. Several differences exist between the two experiments. Unlike the earlier investigation, this experiment used two flight crewmembers involved in each experimental run. In addition, the current study involves a full-mission simulator, while the previous study was run in a part-task environment. Finally, the flight deck implementation of data link is different between the two studies. The first study had a dedicated display of data link, whereas the current study had a data link display that was time-shared with the Flight Management System Control Display Unit (FMS/CDU). There were also other interface differences associated with each of these display differences related to alerting, message access, and responses available.

The data link system that is currently envisioned is considerably different from what was originally examined in much of the previous research (Aeronautical Data Link Integrated Product Team, Human Factors Working Group, 1999). Therefore, the goal of this

research was to re-examine the issues involved in shifting modalities in a mixed media, domestic, en route environment using a current implementation of data link and recommended procedures in a high fidelity simulation. Specifically, we were interested in comparing voice, data link, and mixed ATC environments under time pressure caused by short intervals between messages. Additionally, we hoped to get an early look at how pilots handle more urgent messages in the voice, data link, and mixed environments. We expected that voice communication would be most impacted by the mixed environment and that closely spaced messages would result in more communication problems and longer transaction times and clearance entry times.

## **Method**

### **Participants**

Ten airline pilots (all male) were paid to participate as flight crew members in this study. All participants were either currently type-certified on the B747-400 or retired for less than one year. Average total flight time for the participants was 11,100 hr, ranging from 3,500 to 20,000 hr. Average total flight time on the B747-400 was 987 hr, ranging from 405 to 2,000 hr.

### **Simulation Facilities**

Crews flew in the Boeing 747-400 (B747-400) simulator at the Crew-Vehicle Systems Research Facility (CVSRF) at NASA Ames Research Center. The NASA B747-400 Simulator was built by CAE Electronics and is certified to the FAA Level D certification requirements. Advanced avionics on the B747-400 simulator include two flight management computers (FMCs), three multi-function control display units (MCDUs), Future Air Navigation System (FANS 1/A) data link capability, a Ground Proximity Warning System Unit, and an ARINC Communications, Addressing, and Reporting System (ACARS) Management Unit. Data collection is available for user interaction with all subsystems, including the autopilot system and communication devices.

In addition, the CVSRF is equipped with an ATC Simulation. The ATC system simulated a multi-aircraft, multi-ATC environment. (For a more detailed description of the aircraft simulation facility, see Sullivan and Soukup, 1996).

### **Data Link Functionality**

The simulator was equipped with FANS 1/A data link capability as exists on the 747-400 today (The Boeing Company, 2000). This is an FMC-integrated data link utilizing either of the forward CDUs as an interface. An ATC function key on the CDU keyboard allowed both the Captain and the First Officer access to the ATC data link information on their respective CDUs. Each of the forward CDUs can also be used to interact with the FMC for data input or output (e.g., altitude, route, or speed data). Generally, the Pilot-Not-Flying (PNF) would display the most recent ATC data, while the Pilot-Flying (PF) would remain on an FMC function page.

Upon receipt of a data link message, the visual alert *ATC Message* was displayed on the upper Engine Indicating Crew Alerting System (EICAS) indicating the presence of a message in the queue. A single aural chime accompanied the alert. The visual alert would disappear once the message was acknowledged by a flight crewmember.

An ATC function key was available to both pilots as a hard key on the CDU keyboard. This key was used to access a new message or the ATC Index page if no new messages were in the queue. A method of accessing ATC messages through a menu structure was also available; however, this method was used less frequently since it required, on the average, an extra keystroke by the pilot for message access.

Once a message was accessed, it was displayed on the CDU/CRT (Figure 1). The message page consisted of one or two pages of message content, the text ATC UPLINK at the top, a time stamp representing the time a message was sent, and a page number over the pages

available for the message. In addition, the message acknowledgment options were displayed at the bottom of the message. The acknowledgment options included "ACCEPT", "REJECT", and "STANDBY", and once acknowledged a verify prompt appeared and a second button press was required to downlink the response to ATC. All of these options were selected by using the line select keys closest to the appropriate response.

For a limited number of clearances, there was also a "load" prompt and an "arm" prompt, which would enable the direct entry of the message contents into the FMC. Due to a simulator limitation, crews were instructed to ignore the "load" and "arm" prompts and to enter all information manually.

Other capabilities included in the data link system were the ability to review previous messages and the ability for the pilot to construct and transmit downlink messages to the controller. The menu used to access all ATC activities was titled the ATC Index Menu. This menu page was used to access the ATC Log, ATC Request, and ATC report pages. These other data link capabilities required input through the ATC menu structures displayed on the right and left sides of the display. The ATC Log allowed for an alternative method to access messages upon their arrival into the cockpit, and also was used to access messages that had been previously viewed. The ATC Request and ATC report pages were also used to construct downlink messages to the controller.

### **Instructions and Training**

Participants were given an overview of the experiment and the FAA's current plans for expanding CPDLC in the near future. They were told that the focus of the study was on air-ground communication in the different experimental conditions. They were not briefed on the differences in message interval until after the experiment.



Although all participants were already FANS 1/A qualified, all crews participated in a short briefing and training on the data link system. Based on the recommendation of the aviation community, crews were asked to follow some general procedural guidelines (RTCA, 2000). Specifically, the PNF was asked to handle the ATC communication tasks as is done today, but both pilots were requested to read ATC uplink clearances directly from the display. Crews were also advised as to the relative priority of the different communication media: ATC voice communication was to be handled with the highest priority, followed by ATC data link communication, and finally company communication should be considered the lowest priority. Crews were also instructed that they should respond to ATC messages using the same communication medium (voice or data link) in which they were received. Finally, due to a simulator limitation, crews were asked not to use the "load" or "arm" prompts and to enter clearance data and create reports manually.

After the briefing, the crews participated in a short 30-minute training scenario, in which the crews flew the simulator and operated data link. The procedural guidelines, message alerting, display, and response techniques were explained and demonstrated in detail. Also, the ability to review and downlink data link clearances were demonstrated and practiced.

### **Procedure**

Participants flew a total of six short flights 20–30 min in duration. Each crew flew two legs with voice communication, two legs with data link communication, and two legs with a mix of voice and data link communication. Crews were initialized en route over Salt Lake Center with flight plans to Chicago or San Francisco. Each leg was scripted with a different set of clearances with the help of current and former controllers. Experimenters transmitted the pre-recorded voice and data link messages from the ATC control room, and a retired TRACON controller was available to respond via radio to any pilot communication.

Analyses focused on four pairs of messages (a total of eight target messages) in each scenario. Each of the target messages under investigation contained two commands. The interval between the paired messages was varied: either 5 s or 1 min after the pilot accessed the data link clearance or after the readback of the voice clearance. Because the previous study by McGann et al. (1998) only found problems in the mixed environment when a voice message closely followed data link, and because it is recommended that controllers use voice communication for urgent amendments (RTCA, 2000), we focused on that sequence only. Thus for the mixed environment, data link was always followed by voice. The order of legs, communication medium, and interval was counterbalanced.

FANS 1/A formatting was such that two-element data link clearances could result in either one- or two-page messages. Therefore, for the data link messages, page length (1 vs. 2 pages) was also counterbalanced. Finally, urgency was also varied. Although all target messages defined as normal urgency by the RTCA Minimum Operational Performance Standards (MOPS) document (1993) (no urgent or distress messages were sent), clearances were sent that stopped climbs or descents or asked crews to expedite a turn. The context in which these clearances were sent added a level of urgency, and these messages were systematically varied to allow us to examine the effects of these "urgent" messages on transaction times and clearance entry times. Figure 2 demonstrates how the target messages were constructed to assess medium, interval, order, urgency, and page length in voice, data link, and mixed environments.

This study was designed to assess the effects of communication medium (voice, data link or mixed), message interval (5 s or 1 min), message order (first or second), message urgency, and data link message page length on pilot communication. Three primary measures were collected for each message: the total

transaction time, the time to enter the first clearance directive into the Mode Control Panel (MCP), and number of communication problems (clarifications and errors). Following the experimental runs, flight crews filled out questionnaires about their experiences using each communication medium in the different environments. Additional questions gathered data on pilots' assessments of the data link display, functionality, and associated procedures, as well as the impact of data link in light of other flight duties.

## Results

### Total Transaction Time and Clearance Entry Time

Total data link transaction time included time for the pilot to access the message, read it, and acknowledge it to ATC. Total voice transaction time included time from the controller onset of the message (i.e., the time the experimenter sent the prerecorded message digitally) to the end of the pilot readback including any clarification. These data were collected from the videotapes by two coders. Total transaction times for both data link and voice messages were extended to include any communication by either crewmember with the air traffic controller about the content of the message. These are the operational measures most commonly used for transaction time (Cardosi & Boole, 1991; Kerns, 1991; McGann et al., 1998).

Clearance entry time was defined as the interval from the onset of the digitized ATC message to the time when pilots entered the new clearance data and selected the appropriate mode to initiate an aircraft change based on the new input parameter. This involved entering speed, heading, altitude, or frequency changes into their flight systems. Each clearance transmitted contained two elements, but because some clearances included a request to report reaching an altitude, only the first element entered was used for a comparison across all clearances. For voice clearances, pilots could begin dialing values before the end of the digitized ATC message.

Total transaction time and clearance entry time were each analyzed in a 3 (medium: voice only, data link only or mixed) x 2 (interval: long or short) x 2 (order: first or second message) repeated measures Analysis of Variance (ANOVA). The analysis for total transaction time revealed a significant three-way medium by interval by order interaction,  $F(2, 8) = 4.80, p < .05$ . The analysis for clearance entry time also revealed a significant three-way interaction of medium, interval, and order,  $F(2, 8) = 11.82, p < .01$ . See Figures 3 and 4 for means and standard errors for total transaction time and clearance entry times, respectively. Because the highest order interactions were found, lower level interactions and main effects will not be discussed. To interpret these results, we analyzed the data separately for each environment (voice only, data link only and mixed).

### Comparison of Communication Media

#### *Single medium environments*

Based on the previous study, two hypotheses were generated for the single medium environments, both time pressure and message order would interact in the data link only environment causing the second message in the short interval condition to be lengthened. However, time pressure and message order would not significantly impact message timing variables in the voice only environment.

For each of the two single-medium environments (voice only and data link only), a separate 2 (interval) x 2 (order) repeated measure ANOVA was conducted on total transaction time. For messages in the data link only environment, significant main effects for interval,  $F(1, 4) = 26.91, p < .01, \omega^2_A = .139$ , and order,  $F(1, 4) = 7.86, p < .05, \omega^2_A = .041$ , were identified. Total transaction times for data link messages in the short interval pairing ( $M = 38.05$  s,  $SD = 19.21$  s) were significantly longer than those with a longer interval between messages ( $M = 24.54$  s,  $SD = 7.58$  s). Additionally, messages that were second in the pairing had significantly longer acknowledgment times ( $M =$

34.55 s,  $\underline{SD} = 16.50$  s) than the first message in the pairing ( $\underline{M} = 28.04$  s,  $\underline{SD} = 15.04$  s). In the voice only environment, no significant interaction or main effects were found. It took crews an average of 12.88 s ( $\underline{SD} = 4.95$  s) to acknowledge a voice message in the pure voice environment.

Similar 2 (interval) x 2 (order) repeated measure ANOVAs for the two single-medium environments were conducted on clearance entry time. In the data link only environment, a significant interval by order interaction was found,  $F(1, 4) = 13.80$ ,  $p < .05$ ,  $\omega^2_A = .063$ . The central set of bars in Figure 4 shows that the clearance entry times for the second data link message in the short interval was lengthened, while order had no effect on the long interval messages. In the voice only environment, a significant main effect for order was identified,  $F(1, 4) = 17.06$ ,  $p < .05$ ,  $\omega^2_A = .091$ . It took significantly longer to start entering clearance elements for the first message in the pairing ( $\underline{M} = 11.68$  s,  $\underline{SD} = 6.20$ ) compared to the second messages ( $\underline{M} = 9.48$  s,  $\underline{SD} = 5.29$ ).

#### *Mixed media environments.*

Based on previous research, we hypothesized that the voice messages would be lengthened in the mixed environment under conditions of time pressure. For the mixed media environment, we analyzed total transaction time and clearance entry time in separate 2 (interval) x 2 (order) repeated measures ANOVAs. Recall that in the mixed condition, data link was always the first in a pair of messages followed by a voice amendment. This sequence was chosen for study based on the previous finding that data link followed by voice was the only problematic sequence (i.e. not voice followed by a data link message). Thus, the order of the messages also distinguishes the clearance medium (data link vs. voice). In the analysis for total transaction times, there were main effects for both interval,  $F(1, 4) = 45.00$ ,  $p < .01$ ,  $\omega^2_A = .216$ , and order,  $F(1, 4) = 20.56$ ,  $p < .05$ ,  $\omega^2_A = .109$ . The data link clearances (first message in each pair) resulted in longer transaction times ( $\underline{M} = 37.65$  s,  $\underline{SD} = 18.18$  s)

compared to the voice clearances (second message in the pair;  $\underline{M} = 19.15$  s,  $\underline{SD} = 11.24$  s). It seems that pilots interrupted the data link clearance to attend to the voice message before closing out the data link message. Interval had a large effect on total transaction times (accounting for 21.6% of the variance,  $\omega^2_A = .216$ ), in that a short interval between messages ( $\underline{M} = 36.04$  s,  $\underline{SD} = 20.71$ ) significantly lengthened total transaction times compared to long intervals between the two messages ( $\underline{M} = 20.76$  s,  $\underline{SD} = 9.15$  s).

The analysis for clearance entry time for messages in the mixed environment revealed a significant main effect for interval,  $F(1, 4) = 7.58$ ,  $p = .05$ ,  $\omega^2_A = .040$ , with crews taking significantly longer to enact the first clearance element for the messages with a short inter-message interval ( $\underline{M} = 17.64$  s,  $\underline{SD} = 7.49$ ) than for the messages with a long inter-message interval ( $\underline{M} = 13.35$  s,  $\underline{SD} = 7.78$ ). Interestingly, no main effect for order was found,  $F(1, 4) = 5.59$ ,  $p = .08$ . Unlike total transaction time, crews started entering clearance information equally as fast independent of whether the message was sent via voice or data link in the mixed environment.

In summary, the modality by which a message was sent from ATC to the flight crew affected the time it took crews to acknowledge the message and to begin to enact the control instructions. Total transaction times in the voice only environment were unaffected by time pressure and message order. However, in the data link only environment, we found that time pressure and message order each independently affected total transaction times, with short intervals between messages and subsequent messages having lengthened times. Clearance entry times in the voice only environment showed lengthened times for the second message. While in the data link only environment, clearance entry times were lengthened for the second message in the short interval sequence. When the two message modalities were used in the same flight segment (data link followed by voice), it took

crews significantly longer to acknowledge a data link message compared to a voice message (order effect). Also, time pressure affected both modalities, with longer total transaction times and longer clearance entry times in the short interval sequence.

### Single-Medium vs. Mixed Environments

To further analyze the impact of the mixed environment on communication, we conducted separate analyses to directly compare each medium (voice and data link) in the single and mixed environments. Comparing mixed and single-medium conditions once again required matching transactions in terms of message order. Since in the mixed environment the data link message was always first in the pair of messages, only the first in each pair of messages in the pure data link environment was used in this comparison. We analyzed data link total transaction times in a 2 (environment: pure DL vs. DL in mixed) x 2 (interval) x 2 (page length: 1 vs. 2-page messages) repeated measures ANOVA. This analysis revealed a significant main effect for interval,  $F(1, 4) = 14.22$ ,  $p < .05$ ,  $\omega^2_A = .076$ . As was found in the previous analyses of the data link messages, total transaction times were longer in the short interval pairing ( $M = 39.38$  s,  $SD = 21.11$  s) compared to long interval messages ( $M = 26.32$ ,  $SD = 8.42$  s). No main effects for environment or page length nor any interactions were found.

In addition to total transaction time, we analyzed data link clearance entry times in a 2 (environment: pure DL vs. DL in mixed) x 2 (interval) x 2 (page length: 1 vs. 2-page messages) repeated measures ANOVA. This analysis revealed a main effect for page length,  $F(1, 4) = 83.39$ ,  $p < .001$ ,  $\omega^2_A = .340$ . Page length had a large effect on total transaction times, accounting for 34% of variance. The mean clearance entry time for 1-page messages ( $M = 19.88$  s,  $SD = 5.91$  s) was significantly longer than for 2-page messages ( $M = 13.58$  s ( $SD = 5.75$  s). No main effects for environment or interval nor any interactions were found.

A similar analysis for transaction times was conducted for the voice messages. In this case, voice was always the second in the pair of messages in the mixed environment. Therefore, only the second in each pair of messages in the pure voice environment were used for this comparison. We analyzed voice transaction times in a 2 (environment) x 2 (interval) repeated measures ANOVA. The analysis revealed a significant environment x interval interaction,  $F(1, 4) = 7.60$ ,  $p < .05$ ,  $\omega^2_A = .040$ . Post-hoc analyses indicated that the voice message following the short interval in the mixed-modality environment had a significantly longer total transaction time than the other three message types.

We analyzed voice clearance entry times in a 2 (environment) x 2 (interval) repeated measures ANOVA. It took significantly longer to start implementing clearance information for voice messages in the mixed environment ( $M = 14.24$  s,  $SD = 8.56$  s) compared to the pure voice environment ( $M = 9.48$  s,  $SD = 5.29$ ),  $F(1, 4) = 20.72$ ,  $p < .01$ ,  $\omega^2_A = .110$ .

In summary, we found that the type of environment (pure versus mixed modality) influenced the length of acknowledgement times and time to begin enacting clearance elements for voice messages, but not for data link transactions. For messages sent aurally, total transaction times were significantly longer for messages in the mixed environment when under time pressure (short interval in mixed environment). Clearance entry times were lengthened in the mixed environment compared to the pure voice environment, independent of time pressure. Type of environment did not affect data link timing variables. However, we did find that data link total transaction times were lengthened under time pressure, and time to begin entering clearance information was lengthened for one-page messages compared to two-page messages.

## **Urgent Messages**

As explained earlier, the messages used to convey urgency were not defined as urgent or distress by the MOPS message set, but clearances were sent that stopped climbs or descents or asked crews to expedite a turn. The messages defined as urgent were always the second in the pair of messages, and thus were always voice messages in the mixed environment. This follows the recommended procedure that any non-routine message should be communicated via the voice channel (RTCA, 2000). To examine the impact of urgent messages on total transaction time, we extracted the transaction times for only the urgent messages and conducted a 3 (medium) x 2 (interval) repeated measures ANOVA. The analysis revealed a significant medium x interval interaction,  $F(2, 8) = 30.05, p < .01$ . See Figure 5 for mean transaction times. Simple effects analyses revealed that total transaction times for the second message in a short interval sequences were lengthened in the data link only ( $\omega^2_A = .417$ ) and in the mixed ( $\omega^2_A = .057$ ) environments. However, the impact of the interval manipulation was much stronger in the pure data link environment (accounting for 41.7% of the variance in total transactions times) than in the mixed environment (interval accounting for 5.7% of the variance). Unlike the other two environments, interval had no effect on total transaction times for urgent messages in the voice only condition.

The same analysis was run for clearance entry time, in which we extracted the clearance entry times for the urgent messages and conducted a 3 (medium) x 2 (interval) repeated measures ANOVA. This analysis also revealed a significant medium x interval interaction,  $F(2, 8) = 8.39, p = .01$ . See Figure 6 for means and standard errors. Simple effects analyses revealed that a short interval message significantly lengthened clearance entry times in the pure voice ( $\omega^2_A = .066$ ) and pure data link environments ( $\omega^2_A = .082$ ). However, interval had no effect in the mixed environment.

In summary, urgent messages (ones that contain an amendment to the preceding message) sent via data link suffered both lengthened total transaction time and clearance entry time under conditions of time pressure. The results for messages sent via the voice channel are less clear. For total transactions times, voice messages were lengthened when they quickly followed (short interval) a data link message (mixed environment). However, the clearance entry times for voice messages were lengthened in the voice only environment combined with a short interval.

## **Errors and Clarifications**

Communication problems, such as requests for clarification, were also examined. We hypothesized that the mixed communication environment and short inter-message intervals would produce more communication problems. Communication problems were defined as actions performed by the crew to clarify an ATC message. There were two kinds of actions. First, pilots could call ATC to clarify a voice or data link message (e.g., by asking for a repeat or confirmation). This definition was used in earlier studies of air and ground communication problems (Morrow et al., 1993, McGann et al., 1998). Second, for data link only, pilots could use the review log to clarify message content. Conceptually, use of the review log is similar to voice clarification because the crew performs an action to check or clarify the message. Operationally, they are different because voice clarification ties up the radio frequency whereas review log usage involves only the crew and not the controller.

For this analysis, we wanted to compare the number of voice clarifications across all conditions. However, there were no voice clarifications in the data link only condition, presumably because pilots had the data link review menu available to them, and also there were no clarifications in the short interval messages in the pure voice condition. Therefore, the voice only environment was dropped from the statistical analysis investigating the

impact of interval. Overall, there were 18 voice clarifications and 41 data link "clarifications" (messages reviewed through the review log) in the 240 target messages under investigation. See Table 1 for frequencies of the clarifications across each medium and interval level. A 2 (environment: data link only vs. mixed)  $\times$  2 (interval) repeated measures ANOVA was conducted on the total number of clarifications made by each crew (voice clarifications and data link review menu usage). As predicted, a significant main effect for interval was found,  $F(1, 4) = 90.00$ ,  $p < .001$ ,  $\omega^2_A = .681$ . The short interval significantly increased the number of clarifications.

In order to investigate the impact of medium, the number of clarifications made per crew were summed across the two levels of the interval manipulation. A one-way repeated measure ANOVA was conducted on the number of messages clarified in each of the three mediums (voice only, data link only, and mixed). No significant effect was found,  $F(2, 8) = 2.08$ ,  $p = .187$ . It is interesting to note that only six messages or 10% of all clarifications occurred in the pure voice medium ( $M = 1.2$  clarifications per crew,  $SD = .84$ ). The data link only environment accounted for 46% of the clarifications ( $M = 5.2$  clarifications,  $SD = 1.48$ ), while 44% occurred in the mixed environment ( $M = 5.4$  clarifications,  $SD = 6.07$ ). The large amount of variance in the mixed environment may be masking possible differences between environments.

Additionally, we examined the types of voice communication problems since they may indicate which cognitive processes are impacted by the mixed media environment and time pressure. Voice clarification type included 1) a request to repeat the clearance, 2) a request for confirmation, and 3) incorrect readbacks. Of all radio clearance clarifications, 67% of clarifications occurred in the mixed environment and 33% occurred in the pure voice environment. (Only once in the mixed condition was a data link clearance clarified via the voice frequency.) There were no pilot readback

errors in this study. In the mixed condition, pilots asked the controller for confirmation of a clearance half of the time and the other half of the time requested ATC to repeat the clearance. For the pure voice condition, requests for confirmation of a clearance occurred most frequently (83%) and there was only one request for a repeat of the clearance (17%). These results suggest that crews experienced more difficulty hearing or remembering voice messages in the mixed ATC environment than in the voice-only environment.

Two types of communication errors were coded from the videotapes by two coders. We expected that the mixed environment and short inter-message interval would produce more errors. First, in four cases, crews missed responding to an entire voice message. All of these missed clearances occurred in the mixed environment, three with a short inter-message interval and one with a long inter-message interval. Experimental procedure was to re-send the entire pre-recorded message. In one case, the crew discussed that they would attend to the voice message after finishing the data link message they were working on, but in fact they never did follow up.

Second, in seven cases, crews failed to implement one element of a clearance message. Four times they failed to report reaching an altitude, twice they failed to implement a speed change, and in the final case they failed to engage LNAV, the appropriate mode for the heading change they intended to implement. Six of these seven errors of omission occurred in the mixed environment and one in the pure data link environment. See Table 2 for a breakdown of the errors of omission.

Taken as a whole, the results of clarifications and errors analyses suggests that voice messages in the mixed environment were most likely to be problematic, especially under time pressure. Voice messages in the mixed environment had a clarification rate four times that of voice messages in pure voice environment (taking into account that there were half as

many messages sent in the mixed environment). In addition, most of the missed clearances and messages with implementation errors occurred for voice messages in the mixed environment. Data link messages in both environments (data link only and mixed) had equal rates of clarifications (via the review log), and both suffered when time pressure was present. Crews had by far the fewest problems handling messages in the voice only environment. Total clarification rate in the mixed environment was 4.5 times higher than the voice only environment and was 4.3 times higher in the data link only environment compared to the voice environment.

### **Messages Acknowledged Out of Order**

It is interesting to note that time pressure caused by a short interval between messages sometimes resulted in messages being acknowledged out of order. That is, the second message in a short interval sequence was sometimes acknowledged prior to a response for the first message. Messages were acknowledged out of order in 17 cases (across 240 opportunities). Thirteen of these cases occurred in the mixed environment and four of these cases were from the pure data link environment.

### **Subjective Data**

#### ***Questionnaire Data***

After the simulation, participants responded to a questionnaire and all questions were rated on a five point scale. When asked about the use of data link crews indicated feeling that data link improves the effectiveness of air-ground communication ( $M = 4.10$ ,  $SD = .99$ ) and that they would be satisfied with the data link system as a safety enhancement in the en route phase of flight ( $M = 4.70$ ,  $SD = .48$ ). Pilots also felt that while the data link display was pretty easy to read ( $M = 4.10$ ,  $SD = 1.29$ ), the head-down time required for detecting, reading, and responding to a data link message was only moderately acceptable ( $M = 3.50$ ,  $SD = 1.18$ ). Additionally, pilots indicated that overall the review menu was easy to use ( $M =$

4.10,  $SD = .99$ ). They felt that the review menu was pretty effective for providing a reference to clearances during the pure data link scenarios ( $M = 4.50$ ,  $SD = .53$ ), but only moderately useful during the mixed data link and voice scenarios ( $M = 3.30$ ,  $SD = 1.25$ ).

When comparing the pure medium environment with the mixed media environment, pilots reported that handling voice messages in the mixed environment was more difficult than handling voice messages in the pure voice environment ( $M = 2.80$ ,

$SD = 1.14$ ). Likewise, crews indicated that data link messages in the mixed environment were more difficult to handle than they were in the pure data link environment ( $M = 2.10$ ,  $SD = .88$ ).

Finally, pilots were asked about the specific data link procedures used in the study and they reported that they were comfortable with the procedures ( $M = 4.60$ ,  $SD = .52$ ) and that the procedures were effective for ensuring complete understanding of ATC message content by both crew members ( $M = 4.50$ ,  $SD = .85$ ). Furthermore, the crews felt that the procedures were effective in promoting timely and efficient handling of ATC communication ( $M = 4.60$ ,  $SD = .70$ ) and that the procedures did not interfere with other crew duties related to normal flight operations ( $M = 1.90$ ,  $SD = .88$ ).

In summary, flight crews reported positive attitudes about their ability to use this implementation of data link for air-ground communication in the domestic, en route phase of flight. They reported that the data link functionality and procedures used in this study supported safe and efficient communication with air traffic control. However, pilots did recognize the diminishing value of the data review log and increased difficulty with both types of messages in the mixed environment.

## Discussion

This study extends a previous study by McGann et al., 1998, to better understand how a mixed voice and data link environment affects crew communication. Specifically, the factors of communication modality (voice, data link or mixed), message interval (5 s or 1 min), message order (first or second), message urgency, and data link message page length on pilot communication were evaluated. The principal measures collected were total transaction time, the time to enter the first clearance directive into the Mode Control Panel (MCP), and number of communication clarifications and errors.

While the former study was run in a part-task simulation, the present study allowed us to examine a current data link system (FANS 1/A) in a full-mission environment. Also, this experiment considers the use of data link by two crew members, whereas the previous study examined only a single crewmember. Some differences existed between the data link implementations utilized. The previous study evaluated a dedicated display data link, while this experiment investigated a data link time-shared with the FMC/CDU. There were also variables studied in this research that were not considered in the previous study: message urgency and message length. Thus, this was not a direct replication. However, this study was intended to represent a mixture of voice and data link that is a plausible scenario for near-term data link implementation.

## Medium

It was predicted that closely spaced messages would result in more communication problems and longer crew response times. The results from this study indicate that the time pressure present in closely spaced messages differentially impacted voice and data link.

Direct comparison of the single-medium environments in this study allowed us to determine a baseline of communication performance for both voice and data link. Data link transaction

times were significantly longer than voice transaction times. This is partly due to the data link implementation requiring discrete procedural steps to open and acknowledge data link clearances. However, despite the longer transaction times, it appears that crews usually implement the clearance data prior to acknowledging a data link message. Therefore, data link clearances are often enacted prior to their acknowledgement to ATC. Voice and data link transaction times and clearance entry times were also differentially impacted by time pressure. A short interval between messages significantly lengthened both transaction times and clearance entry times for data link messages, but closely spaced messages had no impact on voice transaction times in the single medium environment. However, an order effect was present in the clearance entry times in the pure voice environment. Thus, the pure voice environment was robust enough to handle a short interval between messages with no impact on acknowledgment times, but time pressure does appear to affect clearance entry time in both data link and mixed environments.

The finding that voice and data link transactions were differentially affected by time pressure replicates the results from the previous study by McGann et al. (1998). Both voice and data link have particular characteristics associated with them. When considering acknowledgment time, voice is the faster and more flexible of the two media while data link has the advantage of message permanence, but is slower and more sequential in nature. However, the timing of the input of data link clearance elements suffers in short interval messages. Since the data indicate that it is the second message in the short interval sequence that is lengthened, this finding is possibly due to the lack of time to complete the data entry for two messages in rapid succession.

It is also interesting to note that data link total transaction time was always impacted by interval, regardless of whether the data link message was in the pure data link environment



or the mixed environment. The sequential nature of the textual data link, which requires a variety of visual and manual tasks, seems to be incompatible with time pressure when responding to a clearance message.

### **Environment**

Based on the findings of the previous study, we expected that voice transaction times would be lengthened in the mixed environment relative to the pure voice environment. Moreover, while we expected that data link messages would be affected by a short inter-message interval, we did not expect the mixed environment to impact data link transaction times or clearance entry times. In fact, we found that both voice and data link transaction times and clearance entry times were lengthened in the mixed environment.

Pilots in the part-task study handled messages sequentially in the mixed environment, completing a data link message before attending to a subsequent voice message, whereas crews in the present study seemed to interrupt the data link message to attend to the subsequent voice message. Recall that the part-task study had a single pilot participant for each of the data collection runs. Despite the different strategies used in the two studies, voice transaction times were lengthened in the mixed environment for both simulations. Procedurally, both crew members were required to read the data link messages from the display, and this could explain why in the present study the PNF did not close out the data link clearance before attending to the voice message in the mixed environment and why the second message in the pure data link environment had longer transaction times compared to the first. These data reflect crew comments that it was more difficult to handle voice messages, in the mixed environment than in the single medium environment.

With regard to message clarification, there were voice communication problems in the voice condition, but not in the data link condition. Some examples of these include

clarification based on the verbal information provided to the crew. As was found in the previous simulation, data link reduced the need for verbal communication with the controller to resolve problems and misunderstandings, largely because messages were permanently stored and available for pilot review. When review log usage was taken as a measure of message clarification, there were more uses of the review log in data link than there were clarifications in the voice environment. This suggests that the textual messages were not easier to remember, they were simply more available for review. Although frequency congestion was reduced in the data link condition relative to the voice condition (6 out of 40 messages were clarified verbally), pilots clarified via voice more in the mixed environment (11 out of 20 voice messages were clarified verbally). Apparently, the value of a review log is diminished when voice and data link messages are mixed. Pilots cannot rely on their data link review log for confirmation of the most recent clearance when many clearances are transmitted by voice. In fact pilots commented that the review menu was only moderately useful in the mixed scenarios. Hence, one of the primary benefits of data link communication, permanent message storage, may be reduced in the mixed environment. In addition, more voice clarification may be required for both verbal clearances and those presented over data link.

Finally, the mixed environment also resulted in more errors than either the pure voice or pure data link environments. Crews were requested to respond to a message in the medium in which it had arrived, so a data link message would necessitate a data link acknowledgment while a voice message would be responded to in voice. However, the controller was always available during each run, so it was possible to respond to a data link message over the voice channel. In four cases, crews missed hearing the entire voice message in the mixed environment. Crews never missed a voice message in the pure voice environment, even with the time pressure caused by closely spaced

messages. Additionally, in seven cases, crews missed implementing one element of a clearance message. All of these errors of omission occurred in messages separated by a short interval. Six of these errors were in the mixed environment while one was in the data link environment. These errors may have occurred because crews sometimes acknowledged closely spaced message out of order. It appears that in switching back and forth between messages, some elements were overlooked.

### **Urgent Messages**

This study also investigated how messages of increased urgency were handled by crews in the voice, data link, and mixed ATC environments. For the purposes of this study, urgent messages were defined as amendments to a previous message. The results indicate that while voice in a pure environment was robust enough to handle time pressure, even urgent voice messages took longer to acknowledge and implement in the mixed environment under conditions of time pressure. Because there was no differential alerting for data link messages, urgent amendments in the data link environment were not readily identifiable and therefore took longer to acknowledge and implement because of the short inter-message interval. Procedurally this raises an important issue because it is often suggested by many within the aviation community that urgent amendments should be handled via voice. However, these data suggest that an urgent voice amendment to a data link clearance is not handled in as expedient a manner as an urgent voice amendment in a pure voice environment.

### **Page Length**

We found no page-length effect for total transaction time whereas 2-page messages actually resulted in shorter clearance entry times than 1-page messages. Further examination revealed that with two-page messages, crews began clearance entry with the first element 17 of 20 times, while for one-page messages they began with the first clearance

element only 12 of 20 times. (These elements were comparable in their content.) One explanation for this result may be that the density of the one-page data link messages was greater than that of the two-page messages causing it to be more difficult to read and leading to longer clearance entry times. The one page messages had all elements of a two element clearance on a single page, usually resulting in about four lines of text for the clearance instruction. Two page messages had those clearance elements split between the two pages. In addition, there may have been some crews who moved more quickly through the data entry of the first element in the two-page messages in the anticipation of the second page. While this may provide a more timely response, it could lead to more confusion regarding that first element due to less careful processing. This finding needs to be investigated further.

### **Conclusion**

Inefficiencies in an overloaded voice radio communication system have galvanized the aviation community to advance the use of data link communication between controllers and pilots to create additional capacity on the voice channel. The implementation of CPDLC throughout the NAS will involve a mixed environment, requiring pilots and controllers initially to switch attention between textual data link and voice media. Some research shows that data link can help reduce transfer of information problems including missed or blocked transmissions (Kerns, 1999). Other studies have shown that a dual-media system requires fewer overall transmissions than the single medium voice system (Talotta, Shingledecker, & Reynolds, 1990).

The results of the present study illustrate what may occur when mixing voice and data link environments under conditions of time pressure. The simulation revealed longer transaction times and longer clearance entry times in the mixed environment than in the pure voice environment. Additionally, flight crews missed entering more clearance data with mixed

voice-data link communication than with either of the single medium conditions. Finally, relative to the pure voice environment, there were more voice clarifications in the mixed environment. When comparing the mixed environment to the pure data link environment, however, the numbers of clarifications (as measured by review log usage in data link) are the same proportionately given that there are more data link messages in the pure data link environment. Again, this seems to be an indication of the added difficulties of shifting between the voice and data link media. Clarifying message content over voice with the controller contributes to frequency congestion and adds workload to the controller.

However, the use of the review log may be problematic since it may not reflect voice amendments and could therefore be inaccurate. In the mixed condition, they are using both methods in an apparent attempt to compensate for some of the possible confusion.

Our research findings substantiate the conclusions from the previous part-task simulation demonstrating that when time pressure is introduced, the mix of voice and data link does not necessarily capitalize on the efficiency of voice and the precision of data link. To ensure the development and use of an effective system, we need to address the human performance concerns for all users in the complex mixed media environment.

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Table 1. Frequency of message clarification types for each level of medium and interval.

	Voice Only		Data Link Only		Mixed	
	Short	Long	Short	Long	Short	Long
Voice Clarifications	0	6	0	0	7	5
Data Link Clarifications	No review log available	No review log available	18	9	9	5
Total Clarifications	0	6	18	9	16	10

Table 2. Breakdown of Clearance Entry Errors.

ATC ENVIRONMENT	OMMISSION ERROR
Mixed Voice, Short Interval	4-Report Reaching, 1-Speed
Mixed Data Link, Short Interval	1-Speed
Pure Data Link, Short Interval	1-Heading (failed to engage LNAV)



Figure 1. CDU display of a single page data link message.

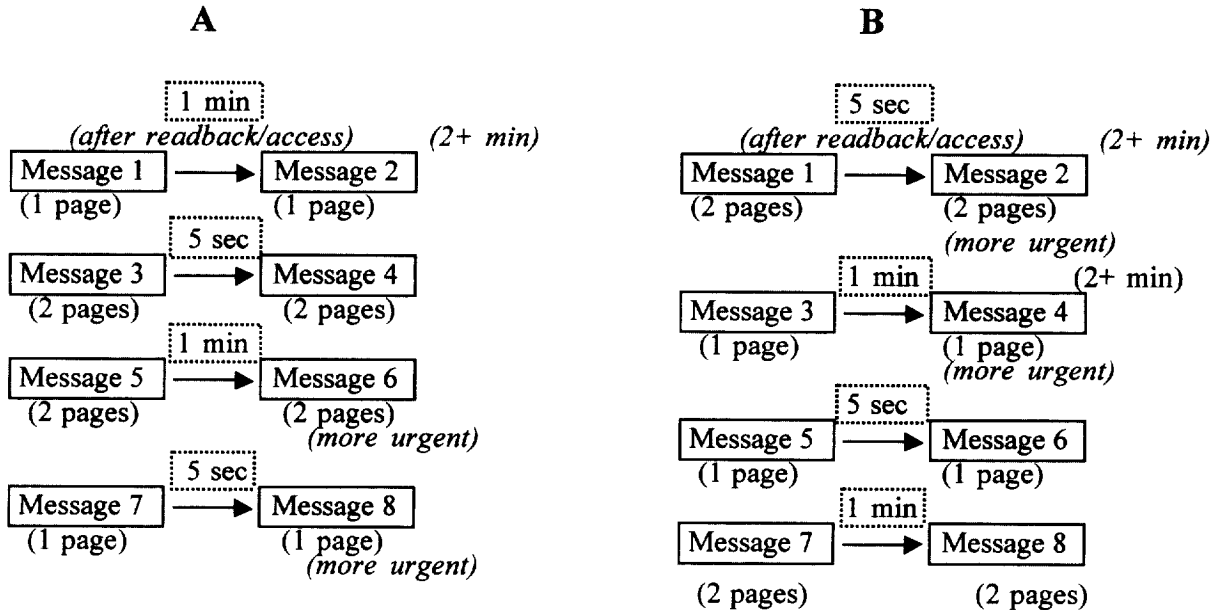


Figure 2. Target messages. All messages contained two commands and all crews flew a version of both Scenario A and Scenario B in pure voice, pure data link, and mixed environments.



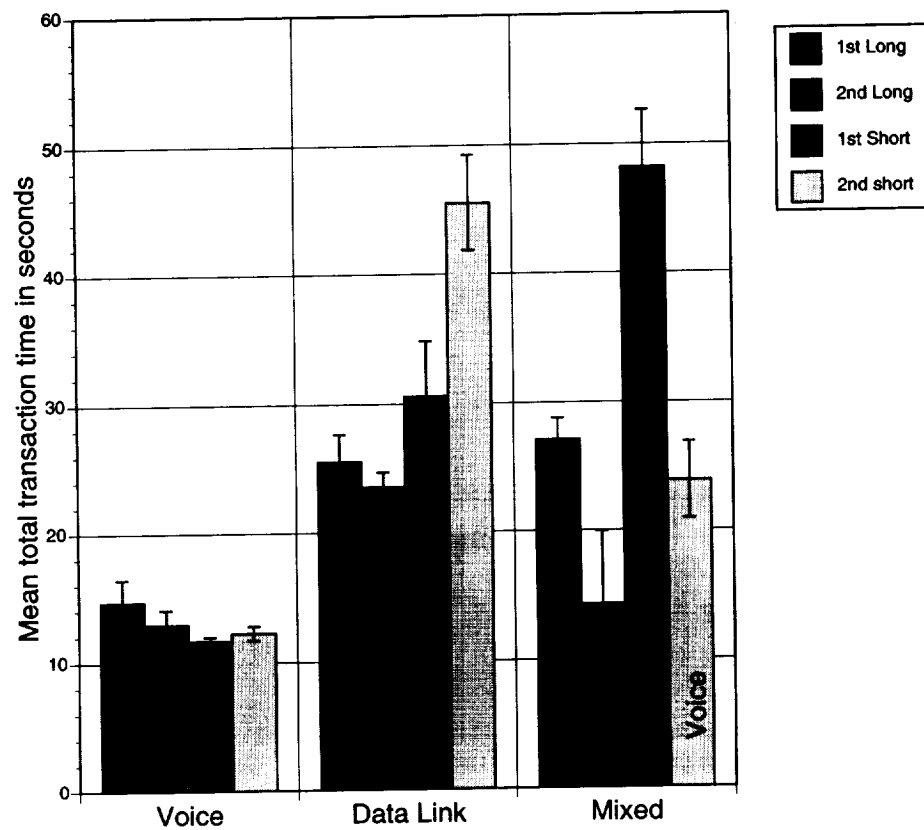


Figure 3. Mean total transaction times for messages by medium, interval and order with  $\pm 1$  SEM bars.

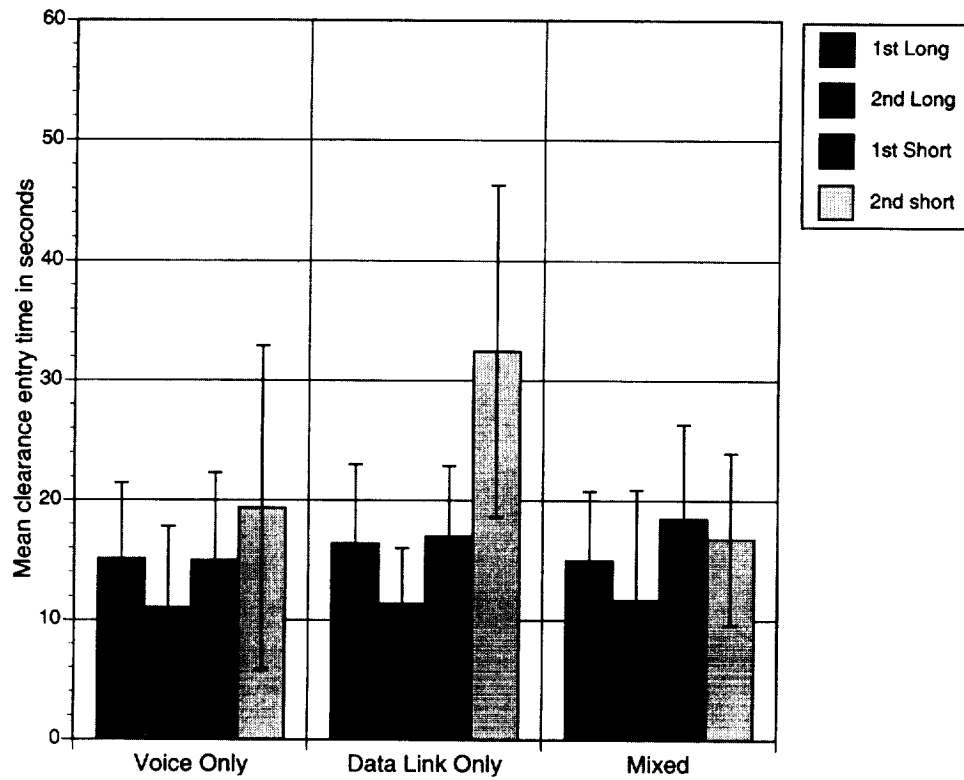


Figure 4. Mean clearance entry times for messages by medium, interval and order with  $\pm 1$  SEM bars.

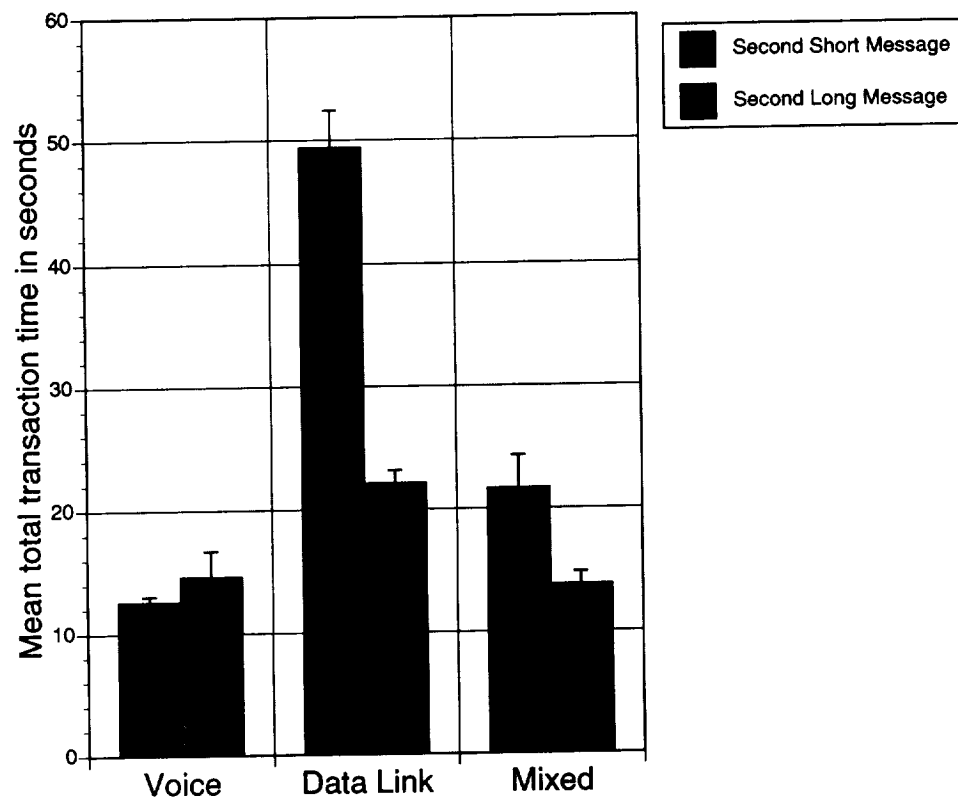


Figure 5. Mean total transaction times for urgent messages by medium and interval with  $\pm 1$  SEM bars.

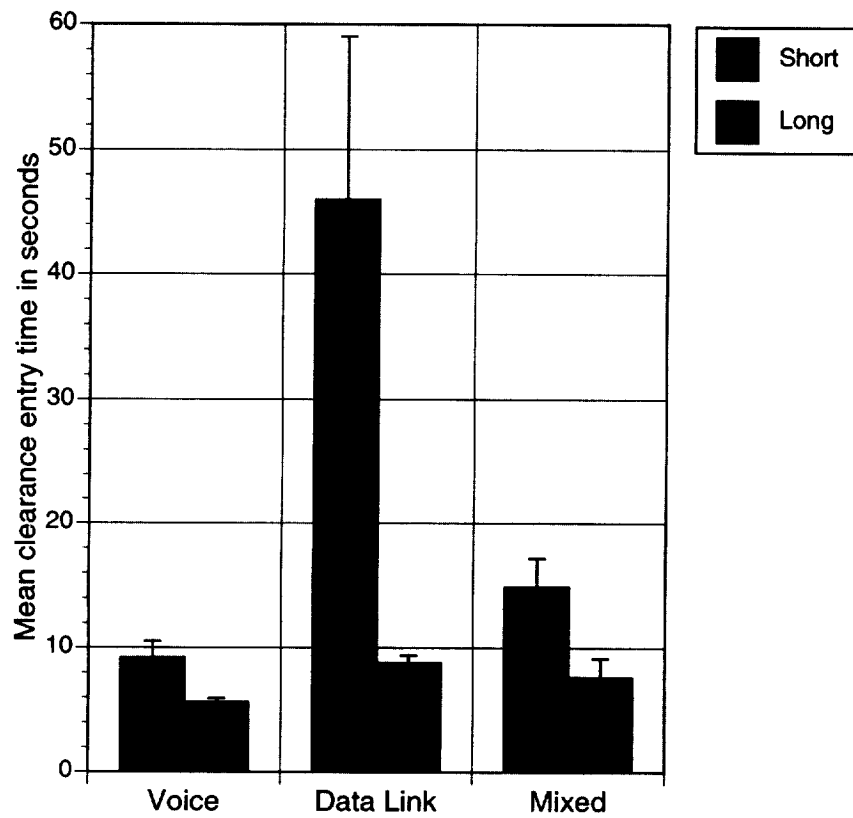


Figure 6. Mean clearance entry times for urgent messages by medium and interval with  $\pm 1$  SEM bars.



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